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Spatial evolutions of inversionless gain and lasing field intensity in an open V-type system with SGC

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ABSTRACT

This paper studies manly spatial evolution of gain without inversion (GWI) and the Rabi frequency E (intensity ε_p) of the probe field in an open V-type three-level inversionless lasing system with spontaneously generated coherence (SGC) for both cases with and without Doppler broadening. We found that: (1) Varying sizes of SGC strength (measured by angle θ), atomic exit rate (r_0) and ratio (S) of the atomic injection rates has remarkable effect on spatial evolutions of GWI and E (ε_p). This effect in the case with Doppler broadening is similar to but weaker than that in the case without Doppler broadening. (2) Regardless of that Doppler broadening is present or not, GWI and E (ε_p) increase with increase of θ, r_0 and S in certain value ranges of θ, r_0 and S; in the case with SGC we can obtain GWI and E (ε_p) much larger than those in the case without SGC, while by choosing values of γ_0 and S, in the open system we can obtain LWI gain and E (ε_p) much larger than those in the corresponding closed system. (3) The propagation distance in which GWI exists in the case with Doppler broadening is longer than that in the case without Doppler broadening; in the case without Doppler broadening, we can obtain larger GWI than that in the case with Doppler broadening; but in the case with Doppler broadening, we can obtain larger E (ε_p) than that in the case without Doppler broadening.

1. Introduction

The generation of lasing without inversion (LWI) is the result of quantum coherence and interference in atomic system. The study of LWI has important theoretical value and application prospect, so it has received considerable attention (for example, see a review paper [1], recent articles [2–5] and references therein). There are many ways to generate quantum coherence and interference. Generally, they can be realized by coherent driving fields or by initial coherence injections, the interference between different spontaneous emission pathways also can lead to the generation of coherence, which is usually called spontaneously generated coherence (SGC). At present, effects of SGC on LWI, the electromagnetically induced transparency (EIT), electromagnetically induced absorption (EIA), optical bistability (OB), etc. have been extensively investigated [6–18]. In the experiment for LWI, usually the active medium is an atomic gas, in this case Doppler broadening is significant and generally will lead to LWI gain deceasing [19–22]. In addition, the propagation effect associated with driving field depletion along the active medium is another important factor to reduce LWI gain (also called as gain without inversion (GWI)). Mompart et al. [23] have studied influence of propagation effect on LWI in a closed V-type three-level LWI system with Doppler broadening but without SGC, they found that by adjusting strength of the driving field at the entrance of the medium, enhanced LWI gain can be obtained. In order to get larger LWI gain and output, investigating modulation role of SGC on propagation effect under the condition of Doppler broadening presenting is necessary. So far, to our best knowledge, there is not such study. In this paper, we will do this work. We will mainly study effects of SGC and Doppler broadening on propagation, i.e. spatial evolution of gain and the Rabi frequency (intensity) of the probe field in an open V-type three-level LWI system and show difference between the open system and corresponding closed system. In order to see the damage of Doppler broadening on LWI gain, we will discuss two cases with and without Doppler broadening, respectively.

2. System model and equations of motion

We consider an open V-type three-level atomic system, as illustrated in Fig. 1. Transition between the levels $|2\rangle$ and $|1\rangle$ is driven by a strong coherent driving field with frequency ω_c and Rabi frequency $\Omega = \vec{\mu}_{12} \cdot \vec{\varepsilon}_c/\hbar$. An incoherent pump with a pumping rate $2R$, and a weak coherent probe field with the frequency ω_p and Rabi frequency $E = \vec{\mu}_{13} \cdot \vec{\varepsilon}_p/\hbar$ are applied between levels $|3\rangle$ and $|1\rangle$. Ω and E are real parameters, $2\gamma_2$ and $2\gamma_3$ denote the spontaneous

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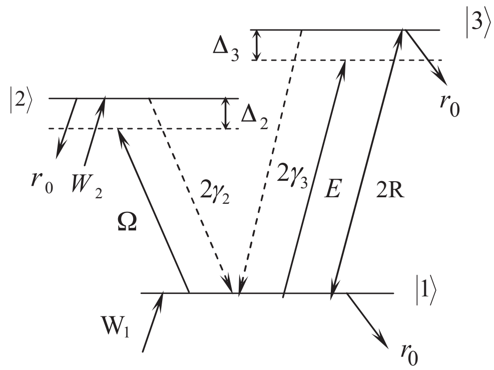

Fig. 1. Open V-type three-level system.

emission rates from level |2⟩ and level |3⟩ to level |1⟩, respectively. The transition frequencies from level |2⟩ and level |3⟩ to level |1⟩ are ω_{21} and ω_{31}, respectively. W_1 and W_2 denote the atomic injection rates to levels |1⟩ and |2⟩, respectively. r_0 is the atomic exit rate from the cavity, and $r_0 = W_1 + W_2$.

Using the slowly varying amplitude and rotating-wave approximations, the density matrix equations of motion of this system can be written as [10,24]

$$\dot{\rho}_{11} = 2\gamma_2\rho_{22} + 2\gamma_3\rho_{33} - r_0\rho_{11} - i\Omega(\rho_{12} - \rho_{21}) - iE(\rho_{13} - \rho_{31}) + 2R(\rho_{33} - \rho_{11}) + 2p\sqrt{\gamma_2\gamma_3}(\rho_{23} + \rho_{32}) + W_1 \tag{1a}$$

$$\dot{\rho}_{22} = -(2\gamma_2 + r_0)\rho_{22} - p\sqrt{\gamma_2\gamma_3}(\rho_{23} + \rho_{32}) + i\Omega(\rho_{12} - \rho_{21}) + W_2 \tag{1b}$$

$$\dot{\rho}_{33} = 2R\rho_{11} - (2\gamma_3 + 2R + r_0)\rho_{33} - p\sqrt{\gamma_2\gamma_3}(\rho_{23} + \rho_{32}) + iE(\rho_{13} - \rho_{31}) \tag{1c}$$

$$\dot{\rho}_{23} = -[\gamma_2 + \gamma_3 + R + r_0 + i(\Delta_3 - \Delta_2)]\rho_{23} - p\sqrt{\gamma_2\gamma_3}(\rho_{22} + \rho_{33}) + i\Omega\rho_{13} - iE\rho_{21} \tag{1d}$$

$$\dot{\rho}_{21} = -(\gamma_2 + R + r_0 - i\Delta_2)\rho_{21} - p\sqrt{\gamma_2\gamma_3}\rho_{31} + i\Omega(\rho_{11} - \rho_{22}) - iE\rho_{23} \tag{1f}$$

$$\dot{\rho}_{31} = -(\gamma_3 + 2R + r_0 - i\Delta_3)\rho_{31} - p\sqrt{\gamma_2\gamma_3}\rho_{21} + iE(\rho_{11} - \rho_{23}) - i\Omega\rho_{31} \tag{1g}$$

The above equations are constrained by $\rho_{11} + \rho_{22} + \rho_{33} = 1$ and $\rho_{ij}^* = \rho_{ji}$, where ρ_{ii} ($i = 1, 2, 3$) is the population of the level |i⟩, $\rho_{ij}(i \neq j)$ is the atomic polarization between levels |i⟩ and |j⟩. Δ_2 ($=\omega_{21} - \omega_c$) and Δ_3 ($=\omega_{31} - \omega_p$) are the detunings of the probe and driving fields from their relevant atomic transitions, respectively. $p\sqrt{\gamma_2\gamma_3}$ denotes the quantum interference effect resulting from the cross coupling between the spontaneous emission |2⟩ → |1⟩ and |3⟩ → |1⟩, i.e. SGC effect. $p \equiv \vec{\mu}_{21} \cdot \vec{\mu}_{13}/|\vec{\mu}_{21}||\vec{\mu}_{13}| = \cos\theta$, where θ denotes the angle between two dipole moments $\vec{\mu}_{21}$ and $\vec{\mu}_{13}$, and $0 \leq \theta \leq \pi$. If $\vec{\mu}_{21}$ and $\vec{\mu}_{13}$ are orthogonal, then $\theta = \pi/2$ and $p = 0$, this means that SGC is absent, and Eq. (1) describes an open V-type three-level atomic system without SGC [22,25]. When $\theta \neq \pi/2$, SGC is present, value of θ represents strength of SGC effect. When $W_1 = W_2 = \gamma_0 = 0$, Eq. (1) reduces to the equations for a closed V three-level atomic system with SGC [6,7].

We assume that the driving and probe fields are all linear polarization along z direction. In the slowly varying amplitude approximation, the equations that govern driving and probe propagation can be written as [23]

$$\frac{\partial}{\partial z}\Omega(z) = \frac{3N\gamma_2\lambda_c^2}{4\pi} Im\ \rho_{21}(z), \tag{2a}$$

$$\frac{\partial}{\partial z}E(z) = \frac{N3\gamma_3\lambda_p^2}{4\pi} Im\ \rho_{31}(z). \tag{2b}$$

where N denotes the atom density, λ_c and λ_p represent the probe and driving field wavelengths, respectively.

Up to now, the above discussion has referred to the homogeneous broadening case. In order to account for the Doppler broadening one should consider, in Eq. (2), the velocity-dependent detunings given by

$$\Delta_2(v) = \Delta_2^0 + \frac{\omega_c v}{c}, \tag{3a}$$

$$\Delta_3(v) = \Delta_3^0 + \frac{\omega_p v}{c}. \tag{3b}$$

where v is the atomic velocity toward the co-propagating drive and probe fields, c the velocity of light, and $\Delta_2^0 \equiv \Delta_2(v = 0) = \omega_{21} - \omega_c$ and $\Delta_3^0 \equiv \Delta_3(v = 0) = \omega_{31} - \omega_p$ the normal detunings. We assume that atomic velocity obeys Maxwell distribution:

$$N_v = \frac{N}{\sigma\sqrt{\pi}} \exp\left(-\frac{v^2}{\sigma^2}\right), \tag{4}$$

where σ represents the most probable velocity, and the width of Doppler broadening induced by emission transition at the half-maximum position is:

$$D = 2\sqrt{\ln\ 2}\frac{\sigma}{c}w_p. \tag{5}$$

Considering the effect of Doppler broadening, Eqs. (2a) and (2b) should be modified as [23]:

$$\frac{\partial}{\partial z}\Omega(z) = \frac{3\gamma_2\lambda_c^2}{4\pi}\int N(v) Im\ \rho_{21}(z, v)\, dv \tag{6a}$$

$$\frac{\partial}{\partial z}E(z) = \frac{3\gamma_3\lambda_p^2}{4\pi}\int N(v) Im\ \rho_{31}(z, v)\, dv. \tag{6b}$$

The probe gain (absorption) coefficient corresponds to the imaginary part of ρ_{31}. If Im $\rho_{31} > 0$, the system exhibits gain for the probe field; if Im $\rho_{31} < 0$, the probe field is attenuated. When $\rho_{33} > \rho_{11}$ and Im $\rho_{31} > 0$ are simultaneously satisfied, GWI can be obtained and the probe field becomes a LWI field.

3. Numerical results and discussion

In the following, we discuss mainly the influence of SGC on propagation, i.e. spatial evolution of the gain and Rabi frequency of the probe field and the modulation role of the atomic exit rate (r_0) and injection rates (W_1 and W_2) on the SGC-dependent spatial evolution in both cases with and without Doppler broadening by numerical results from Eqs. (2) and (6), and compare the open system with the corresponding closed system. In the following discussion, Rabi frequencies of the driving and probe fields at the entrance ($Z = 0$) of the medium are $\Omega_{in} = 30$ MHz and $E_{in} = 0.3$ MHz, respectively; $\gamma_3 = 3$ MHz, $\gamma_2 = 3\gamma_3$, $R = 0.7\gamma_3$, $\lambda_p = 780$ nm, $\lambda_c = 780$ nm, $\Delta_2 = 0$, $\Delta_3 = 0$, $N = 2.0 \times 10^{15}$/cm^3. For convenience in following discussion, we introduce the ratio, S ($=W_1/W_2$), of the atomic injection rates.

Let us first consider the influence of SGC on the propagation effect in the case without Doppler broadening. Fig. 2 plots variations of the population difference $\rho_{33} - \rho_{11}$, the probe gain (absorption)